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Aerial view of Pretoria "A" Power Station, showing the "B" Station under Construction.

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Aerial view of Pretoria "A" Power Station, showing the "B" Station under Construction.

Power Supply at Pretoria.

By A. C. HIRST, B.Sc. (Eng.), M.I.Mech.E., M.I.E.E., M.Inst.F.
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The industrial development of South Africa is reflected in the increasing demand for electrical power throughout the Union, a demand which has manifested itself in the placing of orders for steam turbo-generating plant of a total capacity approaching three-quarters of a million kilowatts since the end of the Second World War. In spite of this, demand is still tending to outstrip supply and further expansion of generating capacity continues to be an imperative need.

Typical of this rapid development is the City of Pretoria. It is interesting to record the growth of the electrical undertaking in the capital during the past twelve years.

The increase in the demand for electricity in Pretoria has been described as almost phenomenal, and not without justification as it has jumped from rather less than ninety million units in 1938-39 to nearly three hundred and fifty million units in 1949. This represents an increase of nearly three hundred per cent. in little more than ten years.

The two principal reasons for this growth are industrial development since the establishment of the large Iscor steelworks, and the growth of the city itself, the population of which has trebled in the last thirty years. In addition to this Pretoria has also become more "electricity-minded," as shown by an increase of two hundred and fifty per cent. in the number of electrical appliances compared with an increase of only seventy per cent. in the number of consumers since 1938. The average number of units sold to domestic consumers has nearly doubled in the past ten years.

In anticipation of the increase in demand, plans were drawn up before the war for the completion of the existing "A" station with two 18,750 kW sets. Orders were placed in 1940 but circumstances delayed manufacture until the end of hostilities and the two new sets were finally commissioned in October, 1948, and March, 1949. The commissioning of the first of these two sets on the 19th of October, 1948, was made the occasion of an inaugural ceremony performed on behalf of the Pretoria City Council by Councillor G. A. D. Pocock, Chairman of the Trading Committee, in the presence of the Mayor, Councillor Mrs. Curzon, and other city officials.

The plant was built to the specification of Messrs. Merz & McLellan, Consulting Engineers, under the direct supervision of the City Electrical Engineer, Mr. D. J. Hugo.

The steam conditions chosen for the final stage of the "A" station are 350 lb/sq. in., 800° F. at the turbine stop valve, with a vacuum of 28 in. Hg., at the exhaust flange. The turbines are designed for a maximum continuous rating of 18,750 kW with an economical rating of 15,000 kW.

They are single-cylinder units of the normal "English Electric" impulse type and run at 3,000 r.p.m. Control is by centrifugal governor which operates through the medium of oil pressure on the relay gear actuating the control valves. A main throttle valve admits steam to a batch of nozzles designed to give up to 60 per cent. of the M.C.R. (11,250 kW) and a full-load valve admits steam to the remaining nozzles of the first stage, corresponding to full admission at this stage and to the most economical rating of 80 per cent. of the M.C.R. (15,000 kW). For loads up to the M.C.R. of 18,750 kW a third valve, the overload valve, comes into operation and bye-passes the first four stages of the turbine, admitting steam to the fifth stage.

Oil for operating the relay gear and valves is supplied at a pressure of about 55 lb./sq. in. from the main oil pump which is of the gear type, mounted in the steam end pedestal, and driven

through a single helical gear from the main turbine shaft. Oil for the lubrication of the turbine and alternator bearings is also supplied from the main pump through regulating valves which maintain the pressure constant at about 10 lb/sq. in. Duplicate 100 per cent. duty oil coolers are provided.

Four stages of feed heating are provided, raising the condensate to a temperature of 314° F, before it returns to the boilers. As will be seen from the diagram, the condensate is extracted from the condenser by a single extraction pump and pumped through the air ejector condenser and a drain cooler to recover the heat from the ejector steam and various drains. It then passes into the L.P. heater, which is of the surface type, and thence via the feed pumps into three further heaters, comprising an I.P. heater, an evaporator heater and an H.P. heater arranged in series. These three heaters are provided with an automatic bye-pass valve which permits the boiler feed water to bye-pass them and flow directly to the boilers in the event of trouble causing flooding in any one of the heaters.

A bled steam evaporator with a capacity of 7,000 lb/hour is provided and the connections are arranged so that the vapour produced is used for feed heating in the evaporator heater when the evaporator is in service. Alternatively, this heater can be fed by steam bled from the turbine when the evaporating plant is not in use.

The condensers are single shell, two pass units, each having a total surface of 25,000 sq. ft., and requiring a circulating water quantity of 17,400 g.p.m. The circulating water is obtained from cooling towers via a common aqueduct for the two turbo sets.

The alternators are direct coupled to the turbines and are designed to give a continuous maximum output of 23,440 kVA at 0.8 P.F. 12,000 volts. Air cooling is on the closed cycle, with two fans, each of which is sufficient for loads up to the economical rating, and with an air cooler supplied with cooling water from the main circulating water system.

The main switchgear associated with the final stage of the " A " station is of " English Electric " manufacture, comprising 12 kV metal-clad, compound filled type OLC 2B breakers with a rupturing capacity of 750 MVA. The auxiliary switchgear installed at the same time was also of the " English Electric " air-break cubicle type OB 3 and OB 4.

As stated earlier, the first of the two sets (No. 8 in the station) was started up on the 19th of October, 1948. From then until the end of the year it ran for 1,585 hours and generated 21,123,200 units. In 1949 it ran for 8,560 hours and generated 129,051,900 units.

The second set (No. 9 in the station) was started up on the 25th of March, 1949, and ran for 6,592 hours to the end of the year, generating 100,376,200 units.

Thus, considering 1949 alone, these figures correspond to an operating factor of 97.7 per cent.

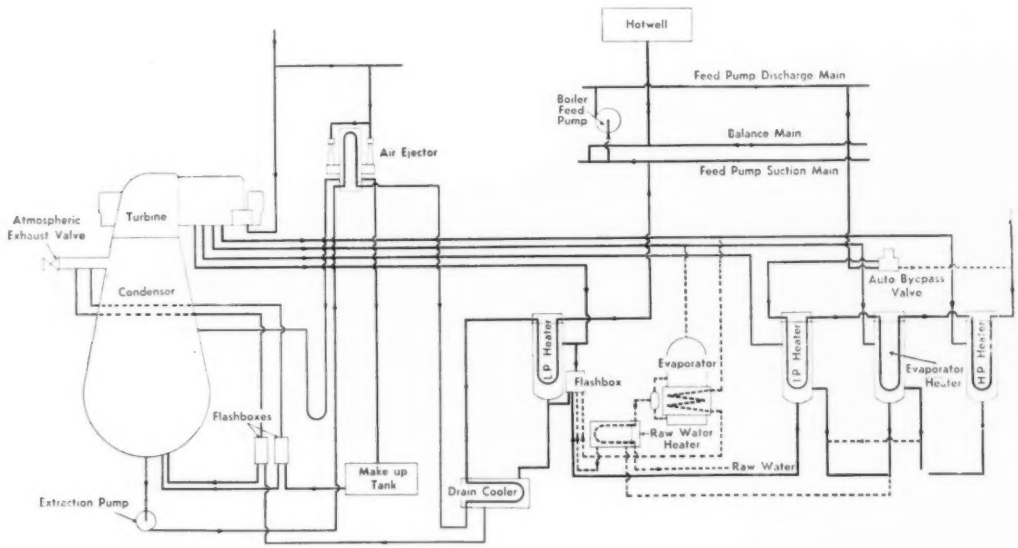


Fig. 1.—A simplified feed diagram.

PRETORIA POWER STATION VIEWS

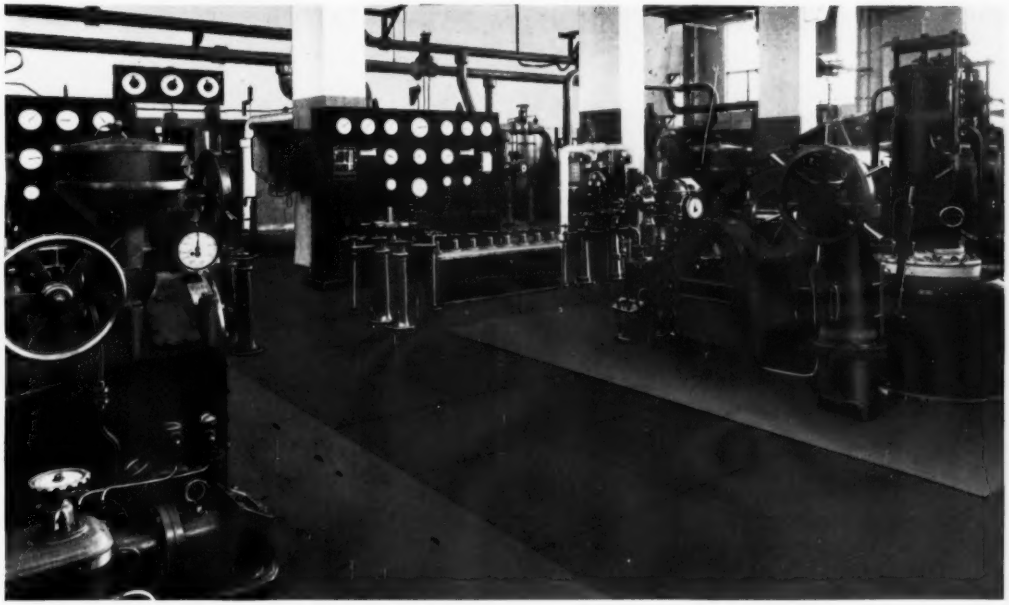


Fig. 2.—View of the turbine floor taken from one side of the centre aisle between the two steam ends of the "English Electric" sets.

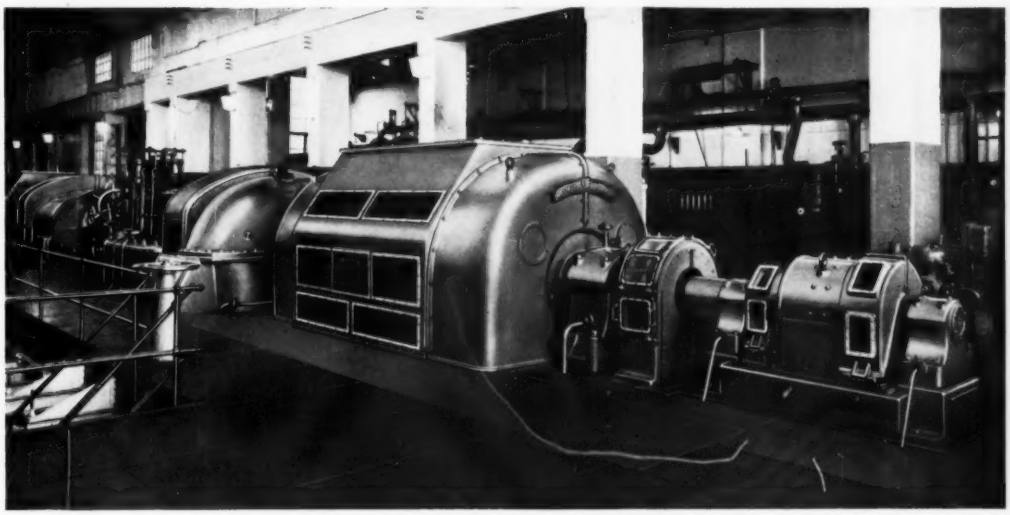


Fig. 3.—A general view taken from one side at the end of the turbine house looking along the two sets.

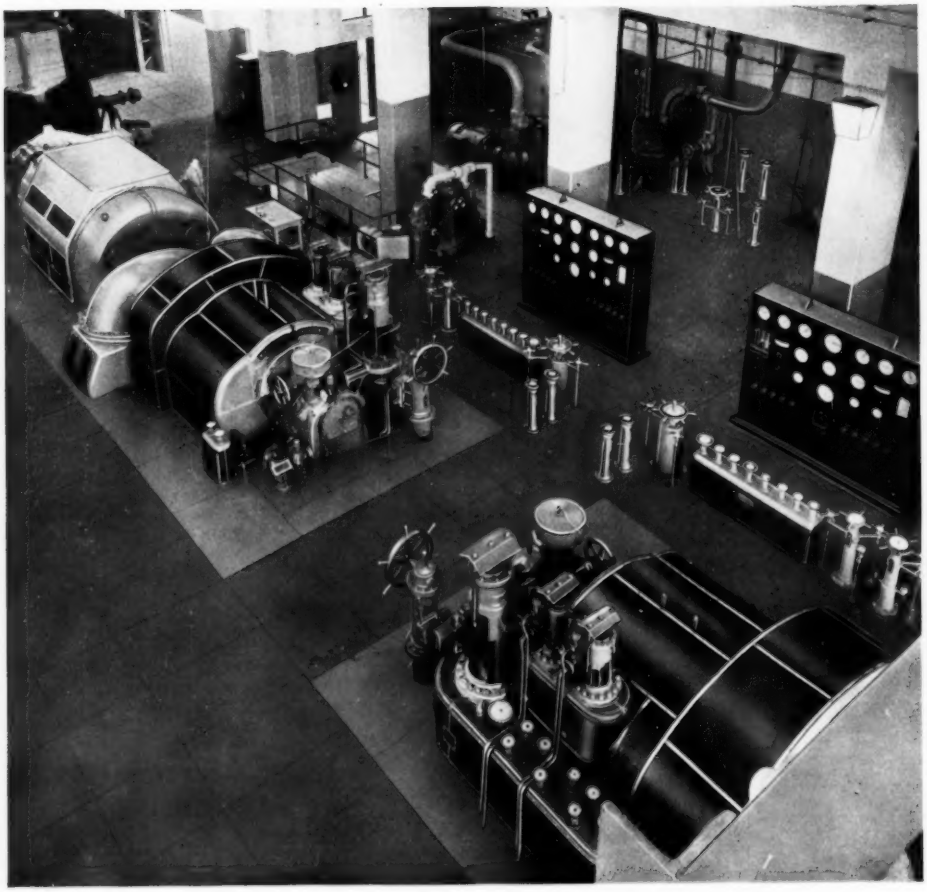


Fig. 4.—A general view of the turbine room.

for each machine, with a load factor of 78.7 per cent. for No. 8 and 79.6 per cent. for No. 9. Data received just before going to Press show that these figures for operating factor and load factor are still being maintained.

New "B" Station.

By the end of the war the rapid increase in demand for electrical power was such as to make it imperative to start work on a new and larger station. Accordingly plans were drawn up in 1946 for the Pretoria "B" station, which will ultimately house six 30 MW sets. Orders have been placed with The English Electric Company for the first three sets, the first two already being in course of completion at site and due for commissioning this year. It is anticipated that the station will be complete by 1956 or 1957.

The steam conditions selected for the "B" station are 625 lb. per sq. in. 825° F. with a vacuum at the exhaust flange of 28 in. Hg. at the economical rating of 24,000 kW. The final feed temperature at economical rating is 340° F. These higher conditions result in an improvement in the overall thermal efficiency of the plant of the order of 8 per cent. as compared with the "A" station.

It is already becoming apparent that even the "B" station will not meet demands for power requirements for more than a few years, and consideration is already being given to the planning of a third and even larger power station.

Cyclotron Power Supplies

The purpose of these notes is to describe some of the power supplies needed for the operation of the cyclotron, originally installed in 1938, which is in use in the Cavendish Laboratory at Cambridge University, for general experimental work on the acceleration of particles and the bombardment of suitable targets with protons and deuterons.

It may first be of interest to give a brief description of the cyclotron itself.

The cyclotron was invented about 1932 by Professor E. O. Lawrence, of the University of Berkeley, California. Its purpose is to accelerate ions (or charged atoms) to velocities about one-tenth the velocity of light, when they become one of the fundamental weapons of the nuclear physicist. Direct acceleration of ions along linear paths requires bulky apparatus and high voltages, and it was to reduce these factors that the cyclotron was devised.

Ions of any velocity in a uniform magnetic field travel in circular paths in a plane perpendicular to the lines of force with a frequency of rotation determined uniquely by the strength of the field. The radius of the orbit depends both on the field and the velocity of the ion. Now ions will only travel freely in a vacuum, so that the first essential of a cyclotron is a large cylindrical evacuated box placed between the poles of a large electromagnet. The box or "tank" is evacuated by the usual rotary and diffusion pumps.

To accelerate the ions, two accelerating electrodes are provided inside the tank. These are flat hollow semi-circular copper boxes mounted so that their straight edges are almost, but not quite, touching. Suppose now that an electric potential difference is maintained between these electrodes (commonly known as dees, because of their shape). As an ion, travelling in a circular path, approaches

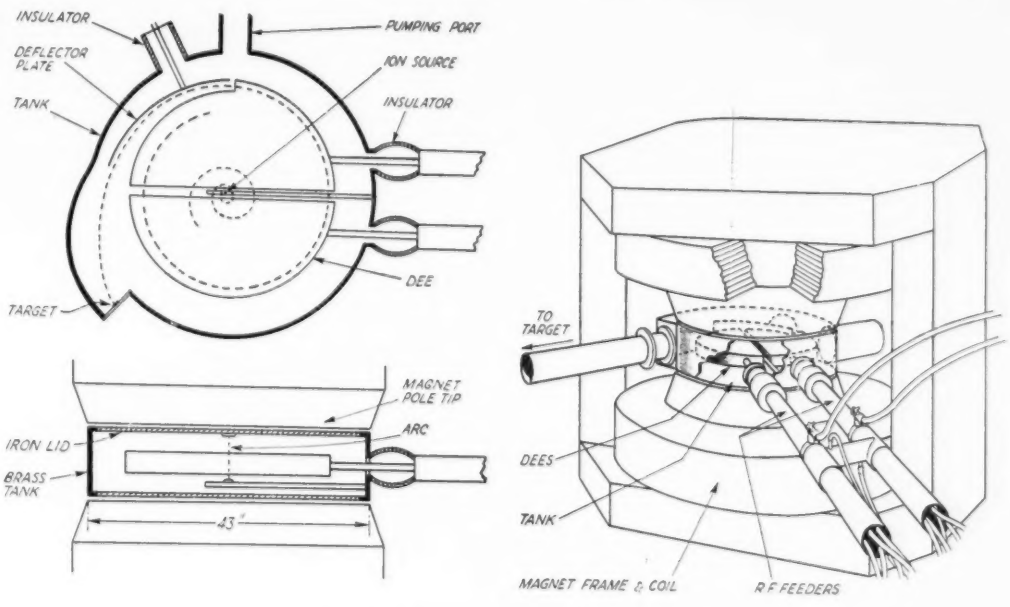


Fig. 1.—A simplified diagram of the essential portions of the cyclotron installed in the Cavendish Laboratory at Cambridge University.

Fig. 2.—The " Dees " which form the heart of the instrument.

the dee gap it is attracted into the opposite dee and thus given an acceleration. Accordingly the ion now travels in a circular path of greater radius, but still with the same frequency. If, when the ion completes a semi-circle inside this dee, the potential between the dees is reversed in direction, then the ion is given a further acceleration as it crosses the gap again. Consequently, if an alternating voltage of the correct frequency is applied between the dees, the ion receives an accelerating impulse each time it crosses the gap. Since the radius of the ion's orbit is proportional to its velocity, the ion is made to spiral outward from the centre of the tank with ever-increasing energy.

Because of the method of operation the cyclotron is often called a resonance accelerator. Its usefulness lies in the fact that quite high energies may be imparted to an ion by means of potentials which are relatively small and easily handled, and also the overall size of the apparatus is conveniently small.

The dees require A.C. power at the correct frequency. This frequency depends on the charge and mass of the ions, and the magnitude of the magnetic field, but it is always in the high radio frequency region. In practice, many cyclotrons operate with a fixed frequency on the dees, and tune the ions to resonance by adjusting the magnetic field strength.

Production of Ions.

The above explains how the cyclotron accepts ions of approximately zero energy at the centre and delivers them at high energy at its periphery. It remains to describe how the ions are produced in the first place, and how they are dealt with at the outside.

At the centre of the tank near its floor is an electrically heated tungsten filament, supported inside a copper tube which extends from the wall to the centre. Hydrogen (or heavy hydrogen) is admitted down the tube and emerges from a nozzle immediately above the filament into the tank. In this way around the nozzle there is a region of relatively high pressure gas suitable for a low pressure arc discharge, while the rest of the tank is at a much lower pressure, so essential for the free movement of ions and maintenance of potentials on the electrodes. An accelerating potential of about 100 volts is applied between the top of the tank and the filament. The electrons from the heated filament ionise the gas and an arc discharge in the form of a vertical narrow pencil through the nozzle is maintained at the centre of the tank. This arc supplies the ions.

At the outer edge, one of the dees has a narrow slot cut in its cylindrical surface through which the ions emerge, though still remaining inside the tank. In order to deflect the ions from their circular path a plate runs parallel to the dee wall for part of a revolution and this deflector plate is held at a high negative potential. This attracts the ions out of their circular path and diverts them into a chamber built as an extension to the tank. The ions finally strike a target at the end of this chamber, and it is here that the nuclear physics experiments take place.

The cyclotron at Cambridge consumes up to 30 kW radio frequency power in the dees and feeders ; the latter being known as an unscreened pair, quarter-wave-resonant, line. This resonant circuit has a high " Q " value and produces about 50 kV between the dees ; even so, almost all the power is dissipated in copper losses. The electromagnet consumes on an average another 30 kW. Both the dees and magnet are water-cooled. The

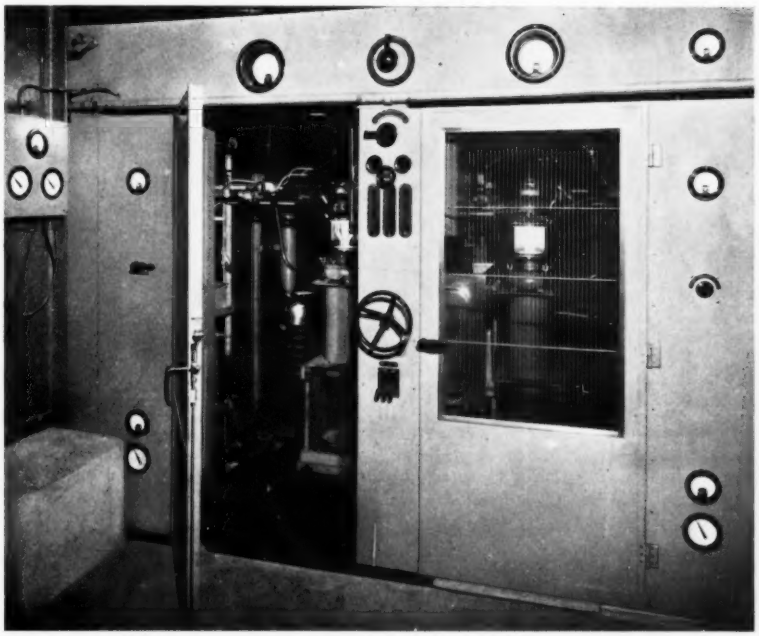


Fig. 3.—The Master Oscillator and first amplifier stages of the R/F section of the Marconi short wave transmitter at the Cavendish Laboratory, Cambridge.

actual ionic current or beam produced is about 30 microamps at 7 million volts, i.e., about 200 watts only of useful power. There is no particular point, however, in computing the power efficiency of a cyclotron. It exists to produce high energy particles, and there is no alternative cheap way of achieving this object.

It will be thus seen that though the operating principle is simple, a variety of power supplies is needed for a cyclotron :—

(*a*) A radio frequency power supply with its frequency easily changeable for obtaining different ion energies.
(*b*) A D.C. power supply for the magnet, readily controlled.
(*c*) A power supply for the arc filament.
(*d*) A high tension negative supply for the deflector plate, variable in magnitude.
(*e*) A D.C. supply to maintain the arc source.
(*f*) Auxiliary power supplies for diffusion and rotary pumps, water pumps and air coolers.

The " English Electric " group of companies has been able to supply the majority of the equipment needed.

Source of High Frequency Power.

It will be apparent from the foregoing notes that the source of high frequency power must be capable of providing extremely accurate frequency control, and the added facility of adjustment to suit particular experiments. Fulfilling all the requirements of such a source of H.F. power is the type TBS801 Marconi short-wave broadcasting transmitter, having a frequency range of 13.5 to 80 metres. At the Cavendish Laboratory a range of 18 to 43 metres is used and the power usually consumed is 35 kW input for an R/F output of about 25 kW (the power factor being assumed to be unity).

The transmitter comprises an oscillator stage and a total of eight stages of amplification. The oscillator consists of a variable tuned Franklin oscillator followed by a multiplier-amplifier rack, this latter portion being air-cooled. The oscillator-drive section is self-compensating for temperature changes, and is constant to within plus or minus 1/20,000. It is continuously tunable.

The next (intermediate) unit is a two-stage amplifier, both stages of which comprise high-efficiency class C circuits. The first stage employs air-cooled valves, and the second water and air-cooled valves. Water for this purpose (and for the cooling of the valves in the final amplifier stage) is contained in a tank mounted above the transmitter units.

Two of the largest valves in the world (Marconi type CAT17C) are employed in a balanced-bridge, push-pull circuit in the final amplifier. These valves are water and air-cooled.

The intermediate and final amplifier stage tuning

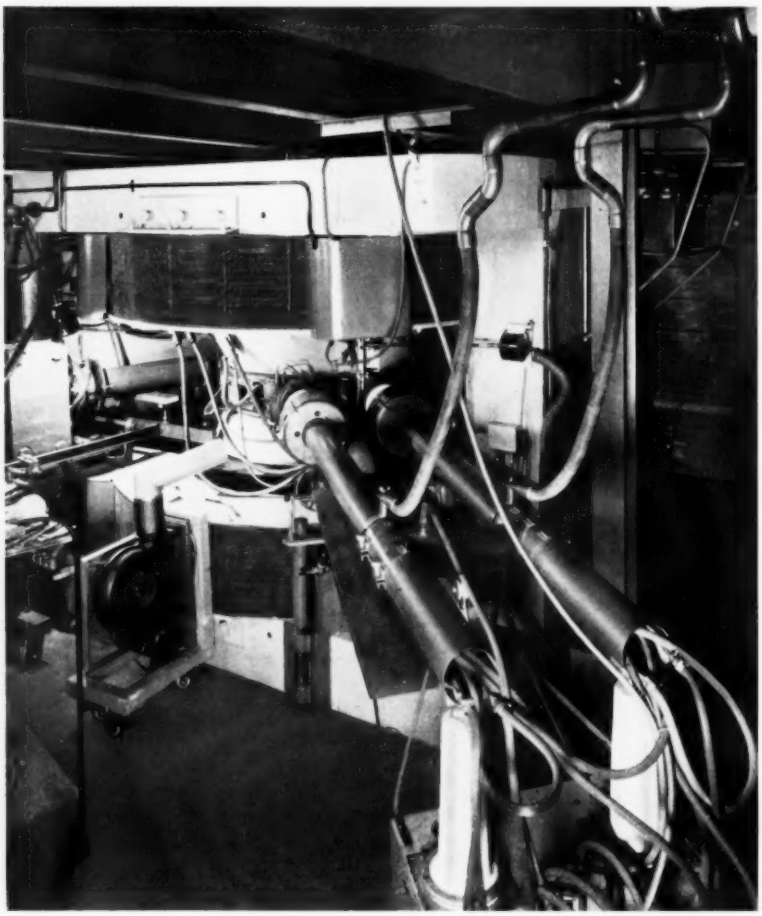


Fig. 4.—A general view showing in the foreground the R F feeders from the Marconi oscillator, and the target tube in the left background.

circuits are mounted on trucks. These can be wheeled into place in the units on guide rails and locked in position with their spring contacts "making" accurately and positively with the fixed circuits. To ensure correct handling of the heavy Type CAT17C valves of the final stage, and to provide rapid replacement, these valves are seated in special mountings. They are withdrawn from or deposited in these mountings by means of a special carriage. This ensures correct alignment of the valves in their seatings.

A pulse modulator has been designed and built by the laboratory engineers to operate at the first signal frequency stage. It provides on-off modulation with a mark-space ratio of about 30 : 1 and an "on" pulse of some hundred microseconds With the modulator working the ion beam is pulsed, and consequently transmutations in the target occur only in regular short bursts. By detecting the products of transmutation at some definite distance from the target, the velocities of the transmutation particles (neutrons) can be measured. This form of operation resembles radar. In the latter, time between pulses is measured and the velocity (of light) assumed, and so distance may be calculated. In a modulated cyclotron distance is known, and time measured, so that velocity (of the neutrons) may be calculated.

The rectifier and its associated transformer and auxiliary gear are of "English Electric" manufacture and are similar to the standard type supplied for use in broadcasting stations in many parts of the world. An equipment of this type is also in use feeding the cyclotron oscillator at Birmingham University.

The rectifier itself is of the six anode air-cooled,

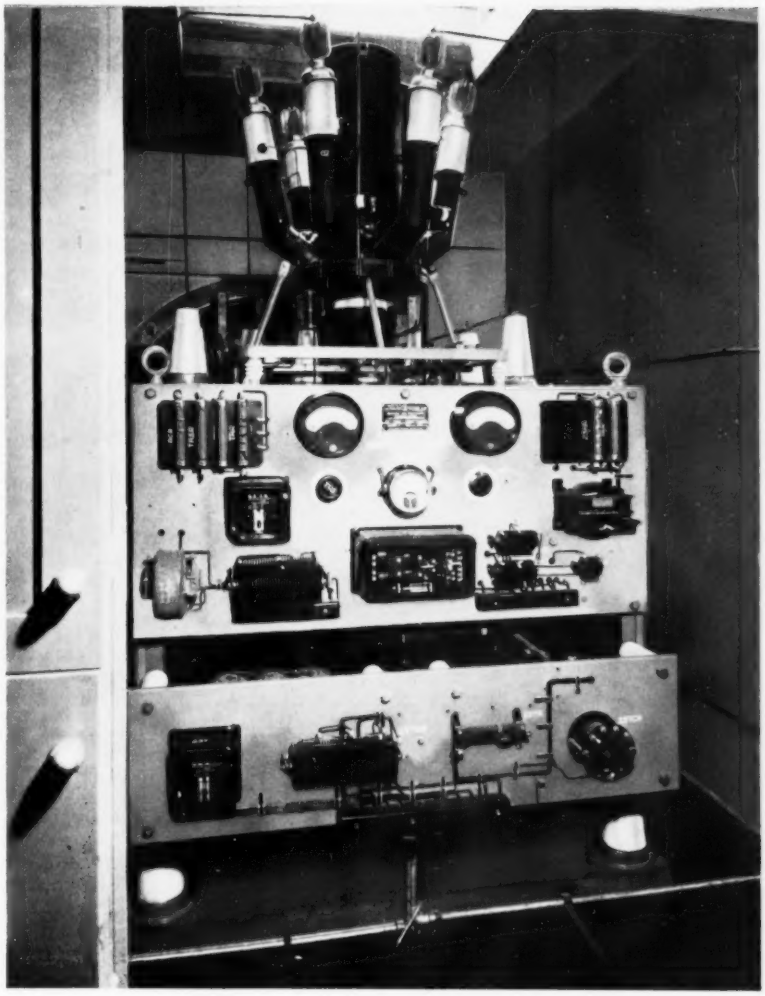


Fig. 5.—The "English Electric" rectifier and its auxiliary equipment, used in conjunction with the Marconi radio transmitter employed as a source of R/F power.

pumpless, steel bulb type and is mounted on top of a square supporting framework which also carries the excitation, grid control and arc suppression apparatus associated with the rectifier.

The main supply to the equipment is controlled by an "English Electric" air-break circuit-breaker from where it passes through an induction regulator to the main rectifier transformer primary. Due to limited space available, the rectifier bulb and its supporting framework are mounted on a gallery above the main transformer and induction regulator.

When grid control of a rectifier is used for voltage variation, the ripple in the D.C. output voltage increases progressively as the degree of grid control is increased, but, due to the rather special operating conditions of the cyclotron which may require long periods of operation at reduced voltage with no more than the ripple of a non-grid controlled rectifier, it became necessary to provide voltage variation by another means. The induction regulator, mentioned above, was therefore supplied and is arranged to give D.C. voltage control between zero and full volts. This is the only major departure in the equipment from broadcasting practice, for which grid control is normally used for voltage adjustment over a small range under working conditions, and from zero to full volts for starting and testing.

For protection against flashovers in the cyclo-

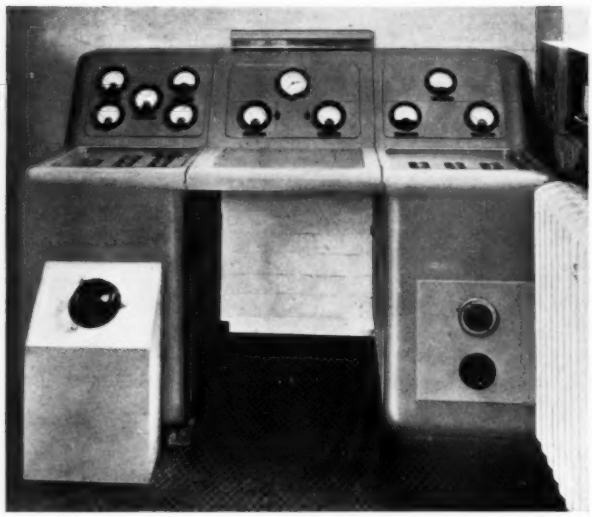


Fig. 6.— The control desk for the operation of the cyclotron as a whole.

tron, heavy overloads, and the like, a high-speed relay with an operating time appreciably less than one cycle from the incidence of the fault to complete clearance is provided, and operates by applying a blocking voltage to the control grids of the rectifier, thus preventing the main anodes from picking up. The relay is fitted with two tripping loops, one loop fed from current transformers in the main supply leads to the equipment, and operating on rate-of-rise of fault current, and the other in the D.C. circuit operating on direct overload. In addition a delay circuit is included which, on starting up or after a trip, only permits the D.C. output voltage to rise slowly, the period being approximately two seconds from zero to full volts after the high-speed relay operates to unblock the rectifier grids.

The next supply to be considered is that for the magnet, where a maximum of 60 kW of D.C. at 300 volts is provided by motor generators in the basement. The magnetic field has a strength of the order of 18,000 gauss.

A further Marconi oscillator is used to energise the filament in the dees. This oscillator provides approximately 1 kW at 1½ megacycles. The deflector plate is supplied by a half-wave rectifier of the glass bulb type with an output of up to 100 kV.

Further auxiliary supplies operating at normal voltages of 346 volts, 3-phase, are used for three oil pumps and the rotary pump which are needed to produce and maintain the vacuum in the tanks surrounding the dees; while the magnet itself, the tank, and the radio frequency feeders, are all water cooled, although here a simple gravity feed is employed without the need of pumps.

Centralised Control.

The control of so many and such varied power sources, particularly with the exactness necessary for research work of the type carried out on the cyclotron, needs to be co-ordinated as far as possible at one central point. The Marconi Company were able to provide a standard transmitter control desk in sheet steel, which was suitably modified to give the operator complete control over the output of the radio frequency transmitter, the filament oscillator, the magnet current (by control of the exciters of the motor-generators through electronic devices) the output of the deflector rectifier, the gas pressure of the in-feed of heavy hydrogen or other gaseous element being introduced into the tank. At the same time the operator can control and check the water cooling of the cyclotron itself and the pumps and air-cooling circuits of the transmitter. By insulating the target and connecting it to earth through a micro-ammeter, the operator can also read the target current.

We are especially grateful to Dr. Kempton and Mr. Ashby, who are closely associated with the cyclotron, and to the University of Cambridge, and in particular the Cavendish Laboratory authorities, for their generous co-operation in the preparation of this article.

Model Tests on Clachan Underground Power Station.

Investigation of Hydro-dynamic Problems in Water Power Developments by Means of Models.

By G. F. W. ADLER, B.Sc.(Eng.), D.I.C., Hydraulic Design Section, Rugby.

Introduction.

During the course of the present century the study of fluid flow problems, particularly as applied to the design of hydraulic structures has, to an increasing extent, been based upon rational analysis.

While rational methods have thus come into their own, they cannot, as yet, form the sole basis of design. Only the most idealised problems can be solved by recourse to them alone. The aim is, therefore, to arrive, in the first instance, at a rational basis, and then to build upon this the empirical structure leading to solution of the given problem.

Model Tests.

The general form of the equation governing a particular system is arrived at by the application of the Principle of Dimensional Homogeneity, a most powerful instrument in such investigations. By its means the various factors involved in the problem are combined in dimensionless groups, each representing a particular aspect of the motion. The extent of the influence of each group must then be deduced by other means. In certain rare cases more advanced mathematical analysis may lead to a solution, but more often recourse has to be taken to actual measurements carried out on a model of the system under investigation.

While such model tests are used extensively to solve basic problems in fluid dynamics, the hydraulic engineer is more often faced with particular design problems, the complexity of which makes it impossible or uneconomical to establish the precise form of the governing equations. In such cases a model test will, nevertheless, lead to solution of the particular problem. Such tests are carried out under conditions determined by the laws of dynamical similarity, which require that in addition to strict geometrical similarity of solid boundaries and fluid paths, for model and prototype, forces acting at corresponding points should bear a constant ratio to each other.

Application to Hydro-Power Schemes.

Used in conjunction with dimensional analysis, model tests of this type, if strictly controlled, are often the only method of solution available

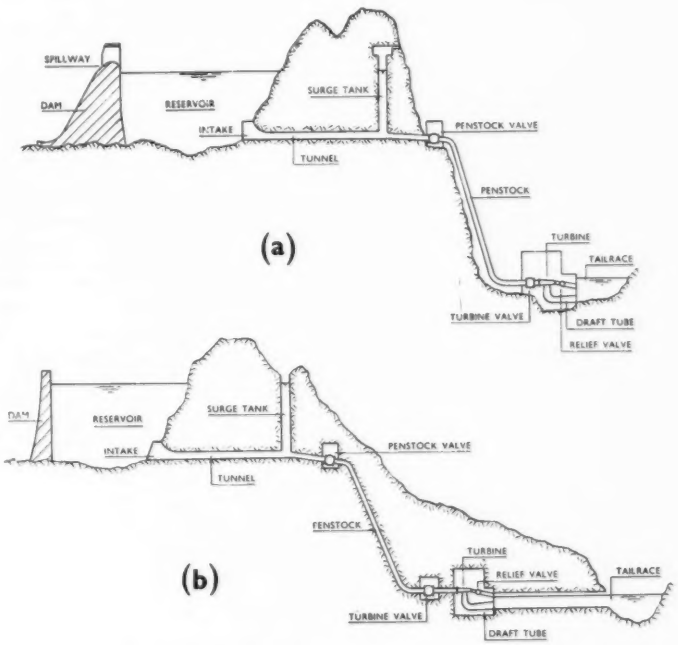


Fig. 1.—Diagrammatic layout of typical High Head scheme.
(a) Power house above ground;
(b) Underground power station.

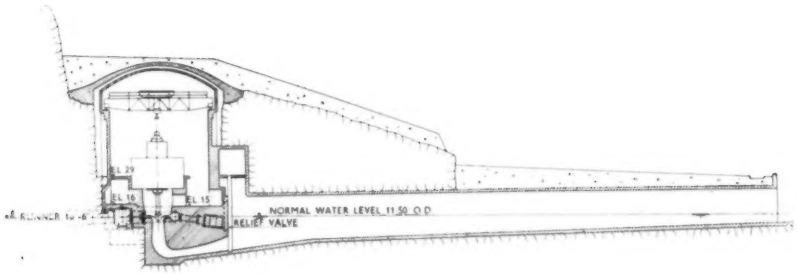
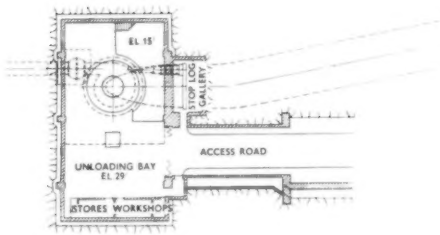


Fig. 2.—Clachan Hydro-Electric Power Station. One 56,000 h.p. Francis turbine, operating under a net head of 930 ft.



for the highly complex systems arising in the design of hydro-power schemes.

Fig. 1 shows in diagrammatic form, two typical layouts comprising dam and spillway, headrace intake and tunnel, surge tank, penstock, inlet valve, turbine and relief valve, tailrace and discharge works. Each of the items enumerated, unless the subject of previous experience, must be thoroughly investigated by either analytical, graphical, or experimental means in order to ensure safe and economical operation of the scheme as a whole.

Instances of the successful application of model technique to hydro-power problems are numerous, the following examples being typical.

Arch dam design, both on the Continent and in America is nowadays widely backed by loading tests on plaster or rubber models. Such tests, particularly in Italy[1]*, have led to striking reductions in material costs without impairing the strength of the structure.

A classic example of successful model tests is the series of experiments conducted on the spillway of Boulder Dam[2]. Flow over the side spillways and through the steep spillway tunnels was investigated on a number of models at different scales.

While analytical and graphical methods for the solution of surge tank problems have been perfected, complementary model investigations can be of great value, particularly in the case of complicated surge systems[3].

Efficiency tests on turbine models, such as carried out in the Hydraulic Test Station at Rugby[4], are standard procedure in the design of the prime mover and these tests may be supplemented by model tests covering such questions as absence of cavitation in the runner, operating forces required for the regulating gear, and draft tube efficiency.

Underground Power Stations.

The increasing popularity of the underground power station (Fig. 1) as a classical solution for medium- and high-head schemes has thrown into prominence the hydro-dynamic problems associated with the design of the tailrace. This type of power station has advantages quite apart from its obvious desirability from the military point of view. In certain cases, indeed, it may be the only economical solution[5].

Owing to the position of the powerhouse, the tailrace must, in such cases, lie at least partly in a tunnel. It can, therefore, be one of three basic types :—

(*a*) Free running under all operating conditions.

(*b*) Under pressure for all operating conditions.

(*c*) An intermediate type, with a surge tank

* Figures in parentheses refer to bibliography at the end of text.

operating only under unsteady conditions of flow.

For any given station the most economic and mechanically satisfactory layout must be determined and such determinations backed by extensive model tests whenever analytical and graphical methods fail to give completely reliable results. Such is particularly the case for the underground station, where the tailrace must be given sufficiently liberal dimensions to prevent flooding of the generators under all operating and emergency conditions, and at the same time be kept as small as possible to reduce excavation costs.

An interesting and exhaustive series of tests in this connection was carried out for one of the earliest underground schemes, that at Innertkirchen, Switzerland[3]. Here, in addition to tests on the upstream surge tank, which is of a complex design, very extensive experiments were carried out to predict the rise of water in the station, resulting upon a failure of the penstock.

Clachan Tailrace Model Tests.

A series of tests recently conducted in the hydraulic laboratory at Rugby were of a somewhat different nature, though also concerned with the study of flow in the tailrace of an underground station.

The Clachan generating station of the Glen Shira scheme (Fig. 2) part of the extensive hydro-power developments in Scotland, will operate under a net head of 930 ft. Its single Francis turbine is designed to develop a maximum of 56,000 b.h.p., the largest figure for any runner in this country. In order to prevent excessive pressure rises in the penstock due to regulation of the turbine, a relief valve discharging directly from the spiral casing into the tailrace is fitted[4]. A sudden closure of the turbine gates automatically leads to a corresponding synchronous opening of the relief valve which thus prevents rapid deceleration of water in the penstock, and subsequent closing at a rate sufficiently slow to keep the pressure rise within safe limits. The changes in conditions resulting from such regulation may lead to the appearance of translatory waves in the tailrace.

It was found in this case that the most economical tailrace layout was of type (*a*). The investigations at Rugby were made at the request of Messrs. Babtie, Shaw & Morton, the consulting engineers, acting on behalf of the North of Scotland Hydro-Electric Board, with a view to determining the minimum tailrace dimensions compatible with this layout, under all conditions of wave formation in the tailrace.

Preliminary Calculations—Model Scales.

The prime consideration in model technique is the choice of scales. Whilst generally speaking, as large a linear scale as possible is to be aimed at, in order to avoid distortion of results due to "scale effect," the feasible maximum is normally determined by reference to costs and available space. With open channel models, such as those of natural rivers, this difficulty is often particularly acute since large horizontal distances are combined with relatively very small vertical displacements and it is the latter which are subject to measurement. A device frequently adopted to overcome this obstacle is an exaggeration of the vertical scale relative to the horizontal. Such a distortion was necessary on a portion of the Clachan model for additional reasons which will become evident later. While the general linear scale 1 : λ, adopted for both horizontal and vertical distances was 1 : 24, the open channel section of the model was reduced in length in the ratio 0.528 : 1, the resulting

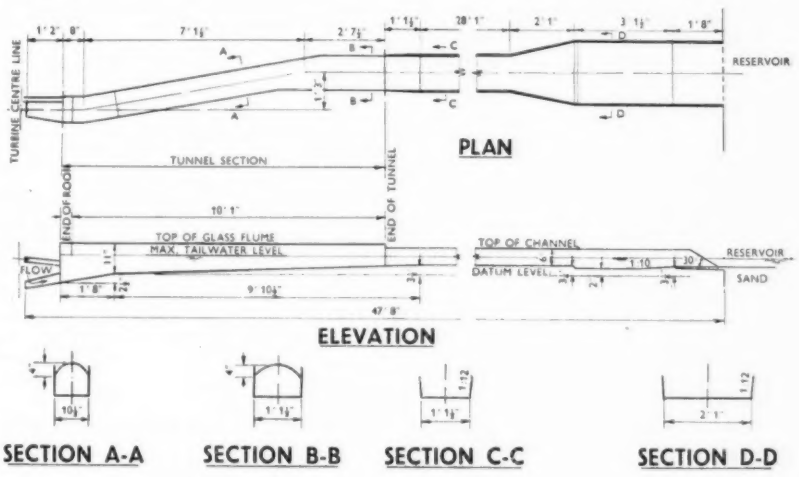


Fig. 3.—Leading dimensions of 1 : 24 linear scale model.

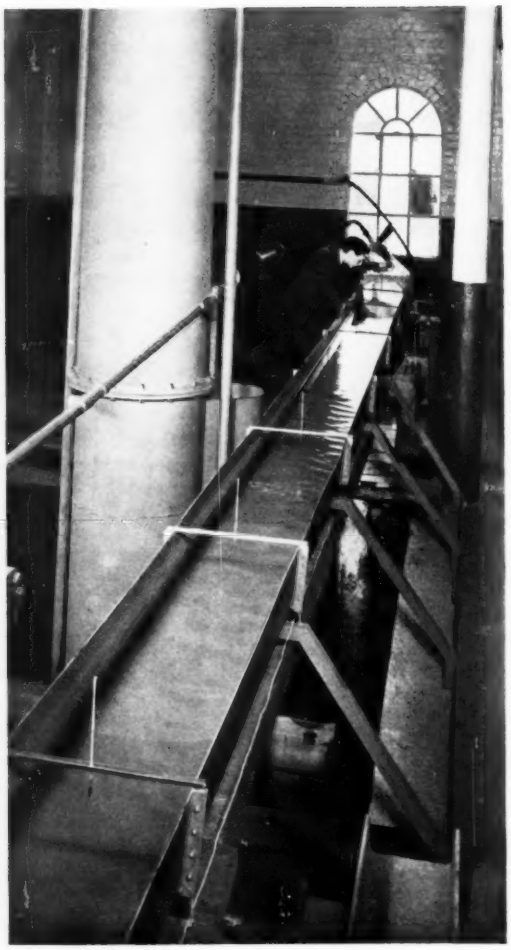


Fig. 4.—Upstream view of open channel section, with wave recorders in position.

length scale therefore being 1 : 45.5. The dimensions of the model are shown in Fig. 3.

Scales of time, velocity and rate of discharge follow from considerations of dynamical similarity. It may be shown that where gravity effects predominate, as in the case of the present model, such similarity is governed by the dimensionless group known as the Froude number, F, which must be numerically equal for model and prototype.

Thus, denoting the model by subscript $_m$,

$$\frac{V_m}{\sqrt{g_m l_m}} = \frac{V}{\sqrt{gl}}$$

where g = acc^n due to gravity
l = typical length
V = typical velocity

Since both model and prototype are subject to the earth's gravitational field, $g_m = g$, the velocity scale is given by

$$\frac{V_m}{V} = \sqrt{\frac{l_m}{l}} = \sqrt{\frac{1}{\lambda}}$$

Time and rate of discharge scales follow from this as $1 : \sqrt{\lambda}$ and $1 : \lambda^{\frac{5}{2}}$ respectively.

Influence of Viscous Forces.

It is not generally possible to ensure at the same time strict dynamic similarity for both inertia and viscous forces. While it is true to say that gravity or inertia effects govern to a large extent the turbulent motion present in such models as that of Clachan tailrace, the possible influence of viscosity must be borne in mind throughout.

It leads to a so-called "scale effect" which, though it cannot be entirely eliminated, may be kept within negligible limits by adopting a sufficiently large model scale.

Roughness Correlation.

Included within the conception of geometric similarity of model and prototype are the surface irregularities of the solid boundaries. It is evident that precise homology in this respect cannot be achieved in practice except in highly idealised cases. The aim is, therefore, to obtain in the model a surface whose resistance characteristics are equivalent to an exactly homologous one.

On the Clachan model, boundary resistance effects were found, by calculation, to assume importance only in the relatively shallow open canal section (Fig. 4) of the tailrace and careful roughness adjustment was consequently confined to this portion. The prototype material is concrete.

Recourse has here to be taken to one of a number of semi-empirical formulæ expressing the mean flow velocity V in terms of a roughness coefficient C, the slope i of the channel invert and r, its hydraulic mean depth. The formula here adopted is due to Manning :—

$$V = Ci^{\frac{1}{2}}r^{\frac{2}{3}}$$

Hence, to satisfy conditions of dynamical similarity,

$$\frac{V_m}{V} = \sqrt{\frac{1}{\lambda}} = \frac{C_m}{C}\left(\frac{i_m}{i}\right)^{\frac{1}{2}}\left(\frac{r_m}{r}\right)^{\frac{2}{3}}$$

$$= \frac{C_m}{C}\left(\frac{i_m}{i}\right)^{\frac{1}{2}}\left(\frac{1}{\lambda}\right)^{\frac{2}{3}}$$

and $$\frac{C_m}{C} = (\lambda)^{\frac{1}{6}}\left(\frac{i}{i_m}\right)^{\frac{1}{2}} \quad \text{.....(i)}$$

Supposing there be no distortion of scale,

$i = i_m$ and $C_m = C \times (24)^{\frac{1}{6}}$

Now for medium rough concrete C = 106 and it

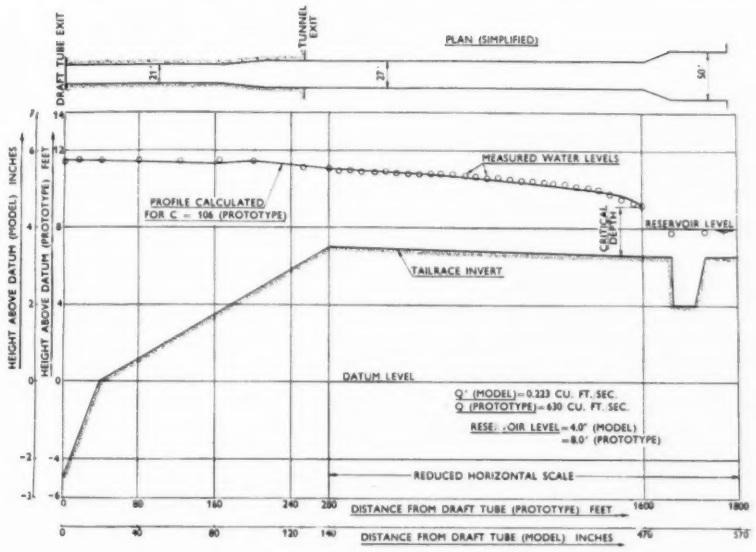


Fig. 5.—Roughness correlation : comparison of calculated and measured water profiles. Prototype flow 630 cusec, reservoir level 8 ft O.D.

follows that for correct roughness $C_m = 106 \times 24^{1/6} = 180$. This represents a surface of a smoothness unattainable in practice. It was thus necessary to adopt a value of $\frac{i}{i_m}$ not equal to unity by exaggerating the slope of the model tailrace. The value of C_m corresponding to the smooth metal and glass construction of the model may be taken as 130. Thus, from equation (i) :

$$\frac{130}{106} = 24^{\frac{1}{6}} \times \left(\frac{i}{i_m}\right)^{\frac{1}{2}}$$

whence $\frac{i}{i_m} = 0.528$.

Scale distortion as applied to this particular case, therefore, arises from the need to reconcile homology of surface characteristics with the use of available construction material for the model.

Water Profile.

While an estimate of the type of surface finish required for the model may be made by use of a flow formula, as outlined above, the final roughness adjustment must be carried out by reference to tests on the model itself. The water profile in the prototype tailrace of Clachan under given steady flow conditions was calculated. The conditions chosen were maximum turbine discharge and a sufficiently low downstream level to produce critical depth in the canal. These were subsequently reproduced in the model and the water profile measured. The model roughness was adjusted until prototype and model profiles corresponded. A comparison of calculated and measured profiles, after final adjustment, is

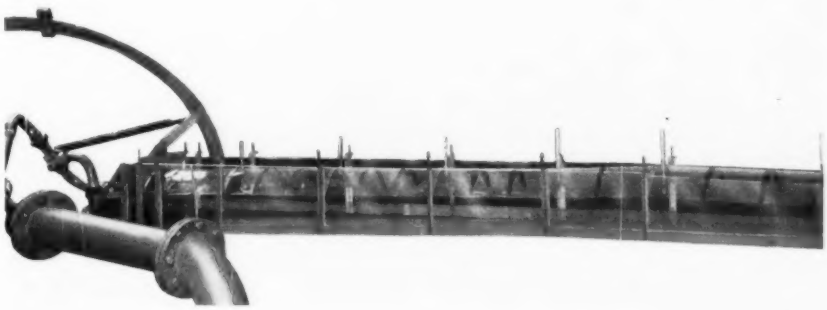


Fig. 6.—Tunnel section showing glass sides and parabolic celluloid roof.

shown in Fig. 5. Exact correlation of boundary drag was thus ensured.

Constructional Details.

The tunnel section of the model tailrace was constructed of steel and glass (Fig. 6), whereas for the open channel sheet steel was used (Fig. 4). The invert of the latter section was rendered smooth and dead level by the application of a coat of pitch in the fluid state. After setting, the whole channel was tilted to give the required slope.

The general arrangement of the model is shown diagrammatically in Fig. 7. Water is drawn from the sump B and delivered to the upstream end of the model via the pressure equaliser C. A large quantity of water is continually by-passed at D in order to ensure stable operation of the pump A.

Flow is directed by the three-way cock H into either the model draft tube or the relief valve (Fig. 8) via the throttling valves J and K respectively, and thence passes into the tunnel section L, the open channel M, and a downstream reservoir N.

The water level in this reservoir, which represents the River Fyne in nature, is controlled by means of a side spilling overflow weir of an effective length sufficient to ensure stability of the water surface.

In order to facilitate visual observation of wave formation in the model tunnel, its sides were constructed largely of glass and the parabolic roof of celluloid sheet (Fig. 6). The height of this roof relative to the invert was adjustable.

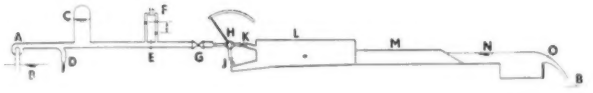


Fig. 7.—Diagrammatic arrangement of Clachan Tailrace Model (see text).

The rate of flow in the model was measured by means of a standard diaphragm E in the supply pipe fitted with a water manometer F. Wave heights were recorded on chemically treated paper indicators mounted on brass strips (Fig. 4) and the waves were timed by electrical contacts on the operating lever (Fig. 8) and on a wave operated aluminium float.

Conditions Investigated.

The Clachan model was used to predict wave formation in the following cases :—

Normal operating conditions—

(*a*) Turbine opening from 0 to 630 cusec. in 20 seconds.

(*b*) Turbine closing with relief valve opening in 2 seconds. Flow constant at 630 cusec.

Emergency condition :—

(*c*) Relief valve opening alone from 0 to 630 cusec. in two seconds.

The latter case presupposes an accidental breakdown of the relief valve operating gear during a shut-down period, leading to sudden opening of the valve superimposed on no-flow conditions in the tailrace.

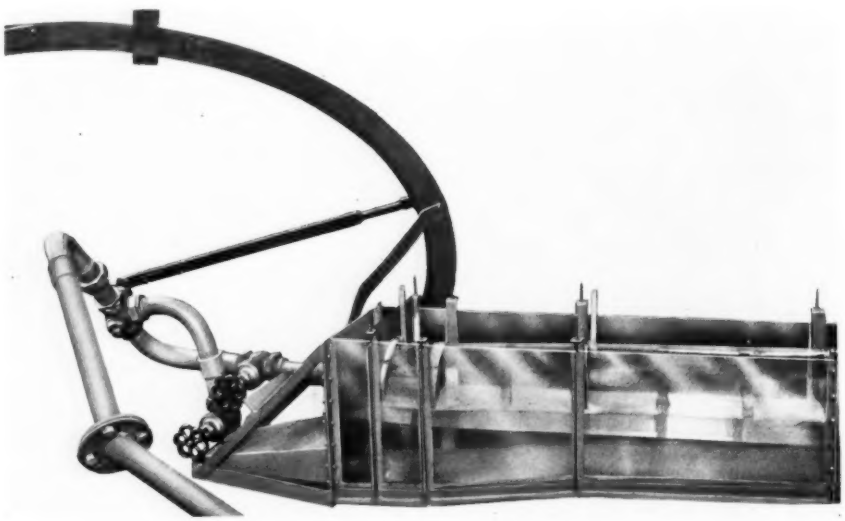


Fig. 8.—View of control apparatus, showing three-way cock, with operating lever, draft tube and relief valve.

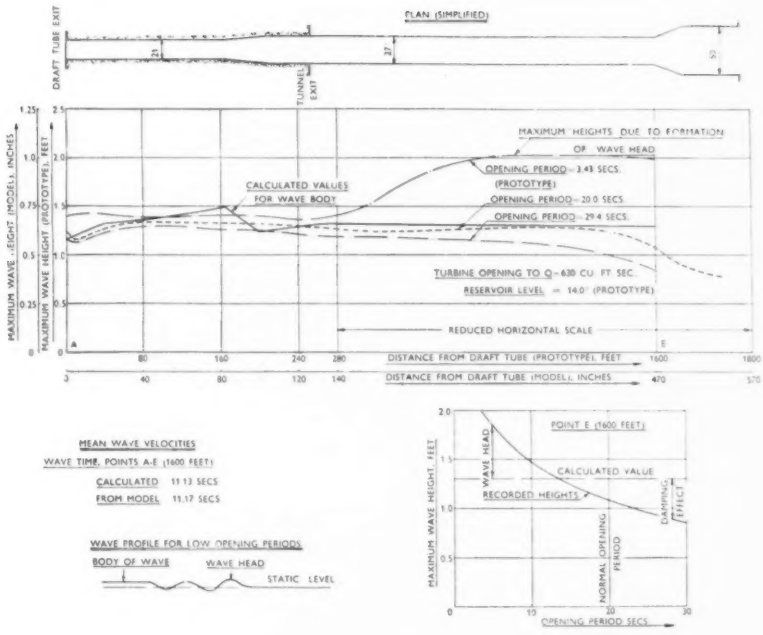

PLAN (SIMPLIFIED)
DRAFT TUBE EXIT
TUNNEL EXIT
MAXIMUM HEIGHTS DUE TO FORMATION OF WAVE HEAD
OPENING PERIOD = 3.43 SECS. (PROTOTYPE)
OPENING PERIOD = 20.0 SECS.
OPENING PERIOD = 29.4 SECS.
CALCULATED VALUES FOR WAVE BODY
TURBINE OPENING TO Q = 630 CU. FT. SEC.
RESERVOIR LEVEL = 14.0' (PROTOTYPE)
REDUCED HORIZONTAL SCALE
MAXIMUM WAVE HEIGHT (MODEL), INCHES
MAXIMUM WAVE HEIGHT (PROTOTYPE), FEET
DISTANCE FROM DRAFT TUBE (PROTOTYPE), FEET
DISTANCE FROM DRAFT TUBE (MODEL), INCHES
MEAN WAVE VELOCITIES
WAVE TIME, POINTS A-E (1600 FEET)
CALCULATED 11.13 SECS
FROM MODEL 11.17 SECS
WAVE PROFILE FOR LOW OPENING PERIODS
BODY OF WAVE
WAVE HEAD
STATIC LEVEL
POINT E (1600 FEET)
WAVE HEAD
CALCULATED VALUE
RECORDED HEIGHTS
DAMPING EFFECT
NORMAL OPENING PERIOD
MAXIMUM WAVE HEIGHT, FEET
OPENING PERIOD SECS.

Fig. 9.—Wave crest heights for type (a) waves, showing influence of rapid openings on formation of wave head. Roof removed, prototype flow 630 cusec., reservoir level 14 ft O.D.

Type (*a*) Waves :

Of the three conditions examined, only case (*a*) readily lends itself to mathematical analysis. The method used[6] is based on the assumptions of uniform velocity distribution and small wave height. Consideration of momentum change leads to the relations

$$\Delta h = \frac{\Delta Q}{\sqrt{gb(A + \frac{3}{2}b\,\Delta h)}}$$

and $$w = \sqrt{g(y + \tfrac{3}{2}\Delta h)}$$

where Δh = height of wave body.
w = velocity of wave propagation.
ΔQ = change in rate of discharge.
g = gravitational acceleration.
b = width of channel.
A = cross sectional area of water.
y = water depth.

Wave heights and velocities at various points in the tailrace resulting from opening of the turbine from zero to maximum flow to 630 cusec. were calculated for maximum tailwater level.

Some interesting conclusions may be drawn from a comparison of these calculated values with those obtained experimentally (Fig. 9). It is evident from the above formulæ that the calculated wave heights are independent of the time of opening. While in the relatively deep tunnel portion correlation with the calculations was generally good, short opening periods led to building up of a " wave head " in the shallow open canal (Fig. 9). The mechanism of the formation of this wave head has not as yet been fully analysed. Further investigations into this phenomenon were not made, since it did not come strictly within the scope of the test.

Considerable surface turbulence in the immediate vicinity of the draft tube owing to the formation of a reverse roller with horizontal axis made observation of basic wave heights in this region difficult. The high values recorded are largely due to local " splash." Some levelling out of wave elevations in the region where a calculated peak value was anticipated, was probably due to the damping effect of wave reflections.

Type (*b*) Waves :

Case (*b*) differs basically from both (*a*) and (*c*) in that there is no immediate change in the tailrace discharge, relief valve opening compensating exactly for turbine closing. There is, however, a considerable change of injected momentum, since the relief valve discharges at roughly ten times the velocity of flow from the draft tube.

Since the mathematical analysis outlined above is not applicable to this case, model tests were the only method of approach available. These showed quite clearly (Fig. 11) that no dangerous wave formation resulted, maximum heights recorded being of the order of 3 ft and below the level originally suggested for the tunnel roof at all points.

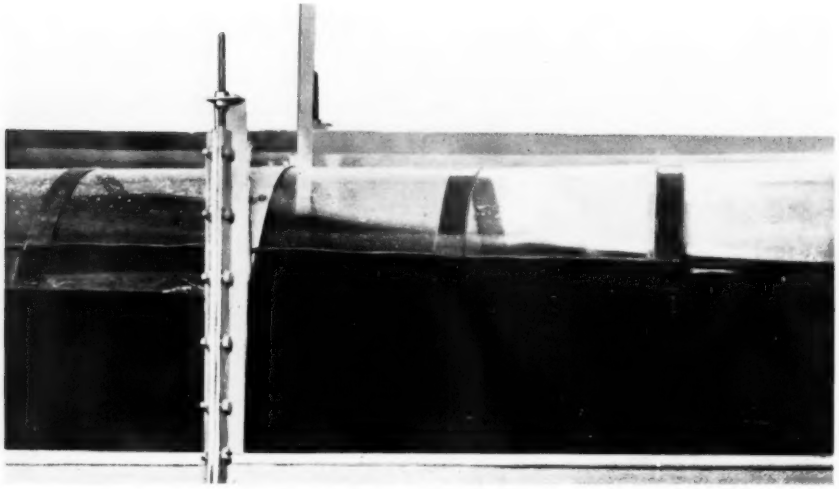


Fig. 10.—Type (c) wave, with 4 ft crest, in tunnel section. The static water level was recorded by double exposure.

It was, therefore, concluded that the tunnel roof could be lowered considerably without endangering the power station. Further tests with the roof in a position 2 ft below that of the original design, confirmed this result.

Type (*c*) Waves :

The final series of main tests investigated the emergency condition (*c*). Owing to the concentrated nature of the discharged momentum, and the formation of a wave-head, this case again does not lend itself to elementary mathematical treatment.

Conditions reproduced in the model were maximum tailwater level, and opening of the relief valve from zero flow to 630 cusec. in the minimum time of 2 seconds, with the tunnel roof at the revised level. The resulting translatory wave is shown in Fig. 10 at a point approximately half-way along the canal. Its height at this point is equivalent to 4 ft in nature.

As shown in Fig. 11, the revised tunnel roof was found to be satisfactory in this case also. The high wave-head would, however, cause overtopping of the open canal banks over a considerable distance.

The mean results of the main test series are summed up in graphical form in Fig. 11.

Auxiliary Tests.

A number of subsidiary tests were carried out to investigate the influence of :—

(i) Negative wave reflections from the reservoir.

(ii) Provision of fish screens at the downstream end of the tailrace.

(iii) Wave resonance.

Conclusions.

The conclusions drawn from the main and subsidiary test series were the following :—

(1) Calculation of wave heights and velocities by the momentum method gives reliable results in cases of reasonably uniform velocity distribution, and of low rates of change of discharge.

The damping influence of friction and wave reflection reduces wave heights slightly below the calculated values in such cases.

(2) More rapid rates of opening or concentrations of discharged momentum lead to the formation of a wave-head preceding the main wave body. The height of this head depends upon the rate of change of injected momentum and may considerably exceed that of the main wave body, to which the above method of calculation applies.

The further investigation of this problem offers considerable scope for basic research.[7]

(3) The three cases of wave formation investigated yielded maximum wave heights and velocities as below :—

	Maximum Wave Height.	Maximum Wave Velocity.
Case (*a*)	1.6 ft	16.2 ft/sec.
Case (*b*)	2.7 ft	17.4 + 3.2 stream veloc.
Case (*c*)	4.3 ft	18.8 ft/sec.

Since the maximum water velocity through the relief valve is in the region of 230 ft/sec., corresponding to an energy of 800 ft. lb/lb, or 56,000 h.p., it is evident that the relief valve effectively dissipates a major proportion of the discharged energy in cases (*b*) and (*c*).

(4) The maximum wave height obtained by

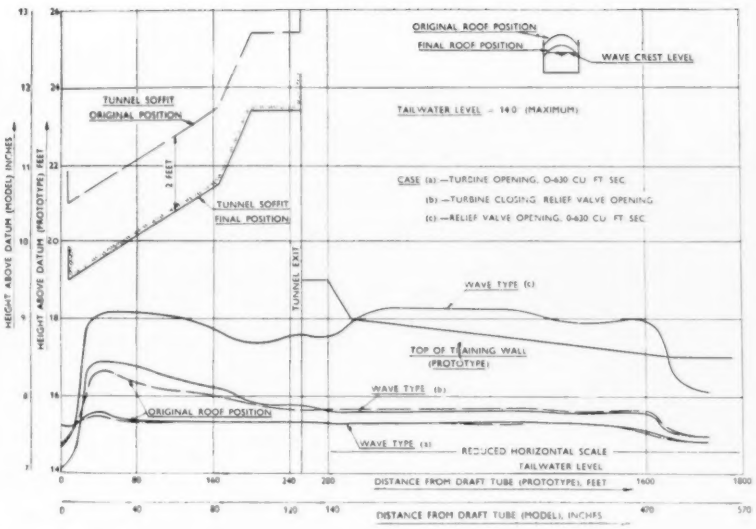

ORIGINAL ROOF POSITION
FINAL ROOF POSITION
WAVE CREST LEVEL
TUNNEL SOFFIT ORIGINAL POSITION
TAILWATER LEVEL + 14·0 (MAXIMUM)
2 FEET
TUNNEL SOFFIT FINAL POSITION
CASE (a)—TURBINE OPENING, 0-630 CU. FT. SEC.
(b)—TURBINE CLOSING, RELIEF VALVE OPENING
(c)—RELIEF VALVE OPENING, 0-630 CU. FT. SEC.
TUNNEL EXIT
WAVE TYPE (c)
TOP OF TRAINING WALL (PROTOTYPE)
WAVE TYPE (b)
ORIGINAL ROOF POSITION
WAVE TYPE (a)
REDUCED HORIZONTAL SCALE
TAILWATER LEVEL
HEIGHT ABOVE DATUM (MODEL) INCHES
HEIGHT ABOVE DATUM (PROTOTYPE) FEET
DISTANCE FROM DRAFT TUBE (PROTOTYPE), FEET
DISTANCE FROM DRAFT TUBE (MODEL), INCHES

Fig. 11.—Summary of results for cases (a), (b) and (c), showing relative positions and influence upon wave heights of the tunnel roof.

reflection from the reservoir was 2 ft in case (*c*). Reflected waves exceeded the height of primary waves only in the immediate vicinity of the draft tube, where the latter were small, due to local depression of the surface.

(5) Fish screens inserted in the downstream enlarged section of the tailrace had a damping effect on the negative reflection of waves from the reservoir. A mean reduction in reflected wave heights of the order of 20 per cent. was observed.

No positive reflections from the screens could be detected.

(6) A rhythmical repetition of case (*c*), producing a condition of resonance, generated waves of greater magnitude than for a single occurrence of case (*c*). Even such extremely improbable conditions, however, failed to lead to flooding of the power house.

As a direct result of the above observations it was possible to adopt a tunnel height 2 feet lower than originally anticipated. This had the double advantage of saving approximately 200 cu. yds. of excavation in rock and of increasing the rock thickness between the tailrace tunnel and an adjoining access tunnel to the power-house. Furthermore, precautions could be taken to prevent damage by overtopping of the canal banks in the highly unlikely but nevertheless possible occurrence of case (*c*).

On economic grounds alone, therefore, the model tests were fully justified. They may be looked upon as an example of the successful application of model technique to a particular problem not fully soluble by analytical means, leading to safe working under the most economical conditions.

ACKNOWLEDGMENTS.

The writer wishes to thank Dr. Ch. Jaeger and Mr. P. Dériaz for their help and guidance, both in the execution of the tests and the preparation of the present article.

Acknowledgment is also made to the North of Scotland Hydro-Electric Board, Messrs. Babtie, Shaw & Morton, and Messrs. Merz & McLellan, for permission to publish the test results.

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Some Traction Machine Developments.

By E. A. BINNEY, Chief Engineer,
Traction Machine Development, Bradford.

For obvious reasons little publicity has been given in this journal to developments in traction machines during the last ten years. In spite of the troubled times of the last decade, some very interesting and practical developments have taken place which have an important bearing on post-war activities, and indeed, some have been adopted during the war period with considerable success. A short review of a few interesting applications may be of some interest.

Light Weight Axle Suspended Motors.

The axle suspended type traction motor has been adopted in this country practically exclusively for motor coach and locomotive drives. The justification for this is to be found in the simplicity of the gear drive employed and of the ease of assembly of the motor on the bogie.

The great majority of railway type motors built before 1930 and still in operation are relatively heavy, slow speed machines. Many of them were designed and built from 15 to 30 years ago, and indeed, it was considered by some authorities to be an advantage to have heavy motors, as their capabilities were based on their heat capacity rather than their continuous rating. In order to avoid insulation failures due to brake shoe dust, these motors are either totally enclosed or only poorly ventilated due to the necessary restriction of the air inlet.

The introduction of the so-called coach ventilated motor permitted the design to be based on high armature speed and adequate provision of ventilating air. In the early 1930's, The English Electric Company established these features as the correct basis for the design of this type of motor. In the years following, a considerable number of relatively high speed, light-weight motors were built for British and foreign railways and have, during the interval, established a high reputation for reliability.

With the axle suspension arrangement, about 50 per cent. of the motor weight is carried on the axle as dead or unsprung weight. In the light-weight motors of the size found suitable for the great majority of applications to motor coaches, this weight is in the order of 1 ton. While this is only about 50 per cent. of the unsprung weight of the older type motor, it nevertheless is advantageous to further reduce the dead-weight on the axle, provided this can be achieved without loss of reliability, since unsprung weight is detrimental in several respects. Not the least of these is the rate of deterioration in the riding quality of the bogie, expressed in reduced comfort to the passengers. With this in mind, The English Electric Company has introduced a light construction suspension bearing cap which reduces the weight of this important component by about 50 per cent. As this weight is entirely supported on the axle, this reduction represents a very desirable achievement. The new "all steel" axle cap, shown in Fig. 1, is designed to provide a large oil well capacity, the oil being contained in the lower portion which is a single piece deep steel pressing. No weld seams occur below the normal maximum oil level.

Fig. 1.—The new "all steel" axle cap

Fig. 2.—The motor incorporates the axle cap, and is designed to provide the same operating characteristics as a motor of 100 per cent. greater weight.

A recently designed motor incorporating this axle cap as well as other weight reducing features, is shown in Fig. 2. This motor is designed to provide the same operating characteristic as an existing motor of 100 per cent. greater weight. Yet its continuous rating is 50 per cent. greater than the latter motor. It is arranged for coach ventilation, i.e., the ventilating air is drawn through the air inlet (which is welded to the frame casting) by way of a bellows connecting to an air duct in the motor coach body.

While, in order to attain the greatest possible saving in weight, various motor components are made of light alloy, no sacrifice in robustness is made where this feature is essential. A large number of motors of this type are under construction at the present time.

Double Gear Reduction Motors.

Two types of traction motors, incorporating double reduction gear drives, have been developed by The English Electric Company in order to meet the exacting requirements of low speed diesel-electric shunting locomotives, a considerable number of which have in recent years been equipped with "English Electric" electrical equipment and diesel engines. The underlying feature of both types is the manner of supporting the intermediate shaft. In both cases, these shafts are carried on double spherical roller bearings supported in bearing housings secured directly to the motor frame casting by means of

Fig. 3.—A 300 h.p. motor with intermediate shaft and first reduction gear train. The pinion of the second gear train is just visible.

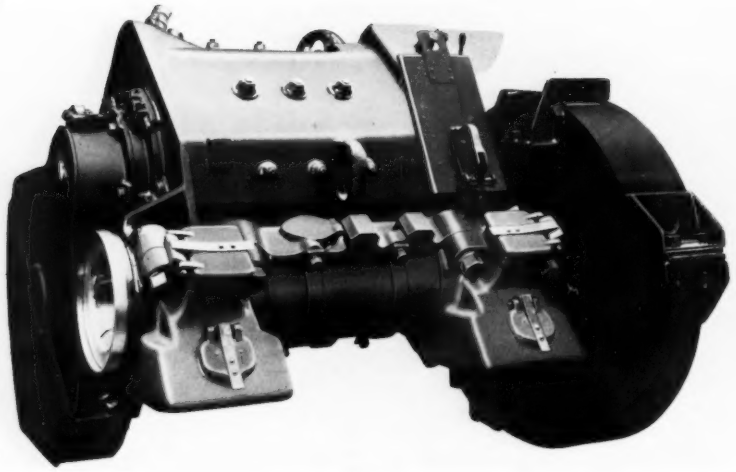

Fig. 4.—A more recent development. The motor is designed as an axle suspended machine with two gear trains having an overall ratio of 21 : 1.

exceptionally robust axle caps. The forces exerted on these bearings and their supports are of a very considerable magnitude and the extremely massive frame of the traction motor provides an admirable support for these bearings. The gear cases are merely required to enclose the gear trains and contain the lubricant, no abnormal forces being imposed on them.

Fig. 3 shows a 300 h.p. motor with intermediate shaft and first reduction gear train, the pinion of the second gear train being just visible. This motor is adapted to be rigidly mounted on the locomotive frame, the second reduction pinion meshing with a gear wheel on a jack shaft also supported on the locomotive frame. The overall gear ratio is 16 : 1. Forty locomotives were equipped with single motors of this type prior to 1939 and a number of these locomotives were used in Africa by the 8th Army, where they gained a very high reputation for reliability.

Fig. 4 shows a more recent development, the motor being designed as an axle suspended machine with two gear trains between the armature shaft and locomotive axle having an overall ratio of 21 : 1. In this case, two motors are arranged on a 3-axle locomotive, all three axles being coupled together by side rods. By arranging these motors for normal axle suspension, while incorporating the double gear reduction, a considerable saving in weight has been achieved.

As the maximum permissible speed of the motors, with the high gear ratio provided, limits the locomotive speed to 20 miles an hour, provision is made for disengaging the gears in order to allow for hauling the locomotive at higher speeds when required.

A considerable number of diesel-electric locomotives with motors of this type have been in successful operation for a number of years, and large orders for further equipments for British and foreign railways are in process of manufacture.

Removable Compensating Windings.

The use of compensating windings on electric traction machinery has in the main been restricted to alternating current motors where their use cannot be avoided. Direct current traction motors can be designed to operate satisfactorily within definite limits without compensating windings. There has therefore been no desire to complicate the motor by the addition of compensating windings, although there are applications in which advantageous operating results would be achieved. However, even in such cases, space limitations usually prevent the introduction of this feature. The space required by machinery carried in the body of a locomotive is not limited to the same extent and the compensating winding can be taken into consideration in the design of the machine in question.

The conventional compensating winding is accommodated in slots in the pole shoes of the machine, the winding being placed in position after the field coils are mounted on their pole bodies. Thus, in the event of a field coil failure, the compensating winding must be stripped in order to give access to the faulty field coil. A further disadvantage is that the access to the compensating winding is restricted by the frame of the machine, which in the case of small machines can be very awkward.

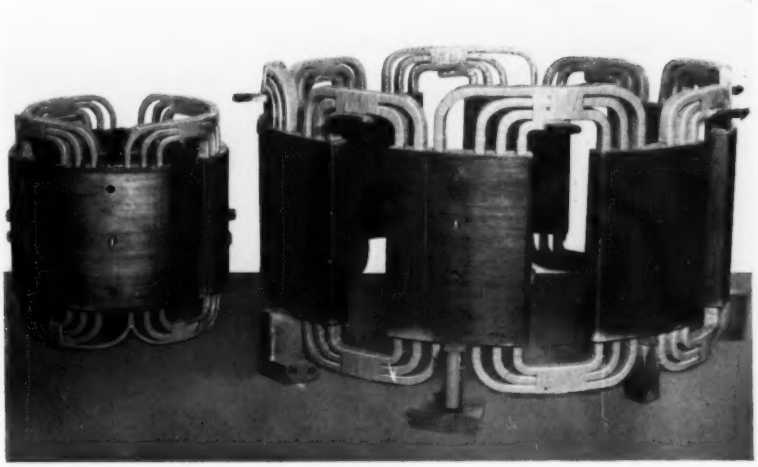

Fig. 5.—Two contrasting sizes of compensating winding. Note that the windings are placed in detachable shoes.

In order to avoid these objectionable features which undoubtedly have contributed in the past to the avoidance of the use of compensating winding. The English Electric Company has perfected a removable compensating winding and has in recent years applied these to a large number of direct current machines of a considerable range in diameters.

Fig. 5 shows two contrasting sizes of compensating windings, one a four pole assembly, the other having eight poles.

It will be noted that the windings are placed in detachable shoes, the actual winding operation taking place with these shoes suitably supported on a winding fixture. All insulating and dipping operations are completed before removal from the fixture.

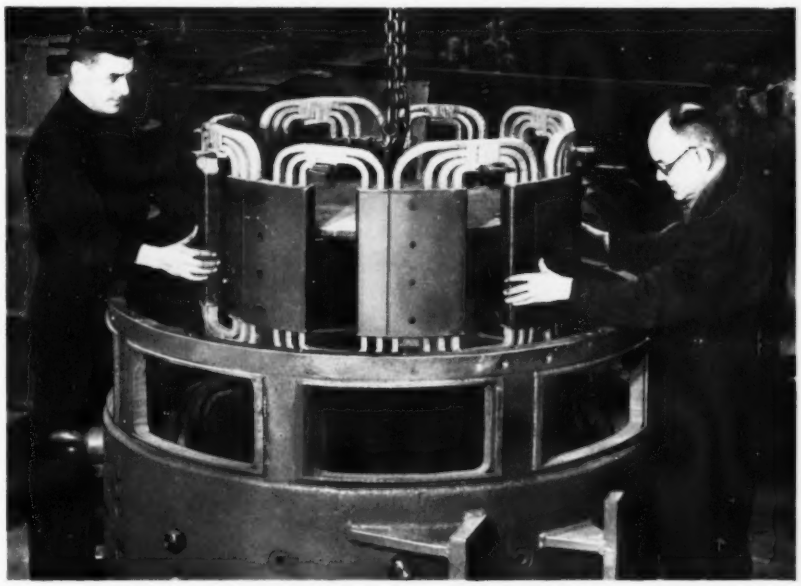

Fig. 6.—The method of assembling a compensating winding into the frame of a 1,200 kW generator for a diesel-electric locomotive.

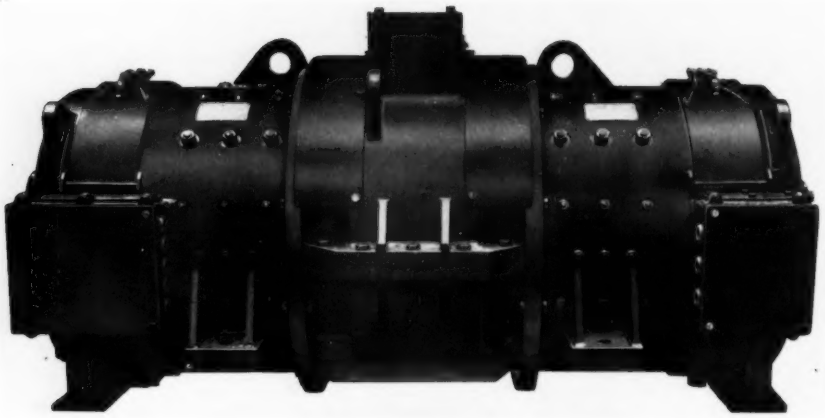

Fig. 7.—A booster set comprising a Direct Current motor and generator with intermediate flywheel.

The completed compensating winding assembly is supported on a suitable mounting fixture and dropped into the correct position in the frame, the pole shoes then being bolted in position.

Fig. 6 illustrates the manner of assembling a compensating winding into the frame of a 1,200kW generator for a diesel-electric locomotive.

A further suitable application of the removable compensating winding is the so-called "booster generator" used in the electric locomotives operating on the southern section of British Railways.

These motor-generator sets, of which there are two on each locomotive, are subjected to very abnormal operating conditions which could not be met without the use of compensating windings.

Fig. 7 illustrates a booster set which comprises a direct current motor and generator with intermediate flywheel. The armature and flywheel assembly is shown in Fig. 8.

Each generator is connected to three traction motors and is so controlled that the desired load current is applied to the motors when at standstill by bucking the line and the desired speed attained by gradually reducing, then reversing the generator excitation.

These locomotives operate on third rail supply and numerous gaps in the third rail must be crossed, during which the supply to the locomotive is interrupted. At this time the booster motor takes the place of the third rail supply, acting as a generator. The flywheel thus drives both armatures during the short intervals of third rail interruption. The motor must thus be capable of sustaining very rapid reversal of current.

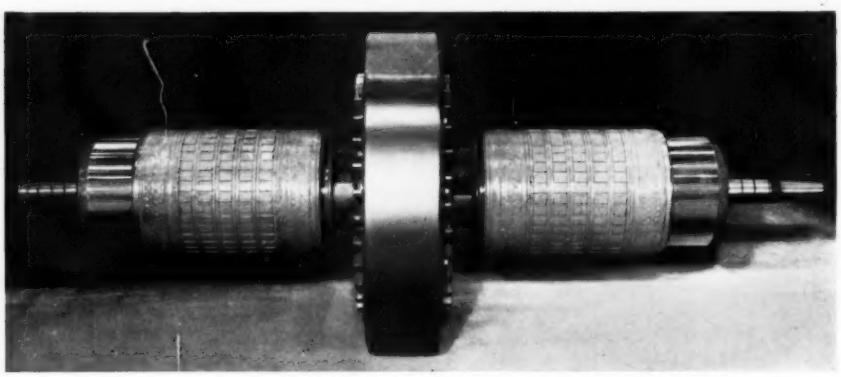

Fig. 8.—An illustration of the armature and flywheel assembly.

Very frequently the third rail may be earthed due to some unavoidable occurrence. Under such conditions, the booster motor is more or less short circuited by this fault resulting in momentary heavy current surges which are in the opposite sense to the motoring current at the instant before the fault. The control equipment provides means for rapidly limiting the current peaks and subsequently clearing the fault. However, the freedom from flashovers under these very severe operating conditions must be largely attributed to the provision of the compensating windings.

The possibility of readily removing and replacing these compensating windings will be recognised as a considerable step towards the removal of any prejudice against their use.